Discovery of an Afterglow Extension of the Prompt Phase of Two Gamma Ray Bursts Observed by *Swift*

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ABSTRACT

Contemporaneous BAT and XRT observations of two recent well-covered GRBs observed by *Swift*, GRB 050315 and GRB 050319, show clearly a prompt component joining the onset of the afterglow emission. The rapid slewing capability of the spacecraft enables X-ray observations immediately after the burst, typically ~ 100 s following the initiation of the prompt γ–ray phase. By fitting a power law form to the γ–ray spectrum, we extrapolate the time dependent fluxes measured by the BAT, in the energy band $15 - 350$ keV, into the spectral regime observed by the XRT $0.2 - 10$ keV, and examine the functional form of the rate of decay of the two light curves. We find that the BAT and XRT light curves merge to form a unified curve. There is a period of steep decay up to ~ 300 s, followed by a flatter decay. The duration of the steep decay, ~ 100 s in the source frame after correcting for cosmological time dilation, agrees roughly with a theoretical estimate for the deceleration time of the relativistic ejecta as it interacts with circumstellar material. For GRB 050315, the steep decay can be characterized by an exponential form, where one e–folding decay time τ_e(BAT)$\simeq 24 \pm 2$ s, and τ_e(XRT)$\simeq 35 \pm 2$ s. For GRB 050319, a power law decay $-d\ln f/d\ln t = n$, where $n \simeq 3$, provides a reasonable fit. The early time X-ray fluxes are consistent with representing the lower energy tail of the prompt emission, and provide our first quantitative measure of the decay of the prompt γ–ray emission over a large dynamic range in flux. The initial steep decay is expected due to the delayed high latitude photons from a curved shell of relativistic plasma illuminated only for a short interval. The overall conclusion is that the prompt phase of GRBs remains observable for hundreds of seconds longer than previously thought.

Subject headings: γ–radiation, γ–ray bursts: GRB 050315, GRB 050319

1. Background

Gamma-Ray Bursts (GRBs) are among the most energetic phenomena in the Universe, and are believed to contain gas with the highest bulk-flow Lorentz factors. GRBs belonging to the "long" class, with duration $\gtrsim 2$ s (Kouveliotou et al. 1993), are thought to herald the death of a massive star possessing high angular momentum, with the additional constraint that our line of sight coincides almost exactly with the rotational axis of the progenitor star. The apparent isotropic equivalent energies of $\sim 3 \times 10^{53}$ erg decrease to $\sim 5 \times 10^{50}$ erg when one corrects for beaming (Frail et al. 2001, see also Panaitescu & Kumar 2001). The prompt emission from GRBs is thought to come from a relativistically expanding fireball (Rees & Mészáros 1992, 1994, Mészáros & Rees 2000, 2001, Mészáros et al. 2002, Piran 2005), likely ejected during the collapse of massive stars (MacFadyen & Woosley 1999, Zhang, Woosley, & Heger 2004). Because of the traditionally long delay between the observations of the GRB prompt emission and the start of the afterglow observations, the exact site of the prompt emission has remained largely unknown. It has been argued that it could either come from the internal shocks (Rees & Mészáros 1994) or from the external shocks (Rees & Mészáros 1992, Dermer & Mitman 1999; for reviews see, e.g., Zhang & Mészáros 2004; Piran 2005). If the prompt emission were due to external shocks, one would see a continuous variation in flux between the prompt and afterglow light curves, with the decay slopes being equal. If it were caused by internal shocks, one should expect distinct components for the $\gamma-$ray light curves and the late afterglow. Looking for the bridge between the early, $\gamma-$ray light curve ($\lesssim 100$ s) and the later, X-ray light curve ($\gtrsim 100$ s) is therefore essential in clarifying the emission site for the early flux. The unique capability of *Swift* makes this possible. In particular, early-time XRT data reveal that early X-ray afterglow shows a distinct steeply decaying component followed by a shallower, more standard decaying component (Tagliaferri et al. 2005, Chincarini et al. 2005, Goad et al. 2005, Nousek et al. 2005, Zhang et al. 2005, Panaitescu et al. 2005).

Prior to *Swift* it was not possible to study the detailed functional form for the decay of the prompt emission because there was not enough of a dynamic range in flux available for detailed quantitative investigation. The finite γ−ray background of large FOV detectors such as BATSE limits the available dynamic range in flux to about two orders of magnitude, except for unusually bright GRBs. For instance, Giblin et al. (1999) examined the BATSE decay light curve of GRB 980923 and fit a decay law of the form $A(t - t_0)^{-n}$, where $n = 1.8 \pm 0.02$. Other workers have carried out similar studies and placed constraints on the decay index: n(GRB 920723)$= 0.69 \pm 0.17$ (Burenin et al. 1999), n(GRB 910402)$= 0.7$ and n(GRB 920723)$= 0.6$ (Tkachenko et al. 2000), and n(GRB 990510)$= 3.7$ (Pian et al. 2001). Also, in't Zand et al. (2001) found a steep fall-off of the $2 - 10$ keV emission of GRB 010222 after 100 s.

Connaughton (2002) co-added the background-subtracted BATSE light curves for 400 long GRBs, and found $n \simeq 0.6$ for the ensemble decay. It is not clear how physically meaningful this averaged value is, given the potential variety of decays for different bursts, and the systematics of the background subtraction for individual bursts. A related issue is that of how to "line up" different GRBs, i.e., the choice of t_0. For instance, if each distinct spike within a multi-spike GRB results from a δ-function injection of energy into a relativistic plasma, the relevant t_0 for times well past the end of the GRB would be the starting time for the last spike. The use of a physically inappropriate t_0 would smear out the results of an ensemble average. There may also be a dependence of the results on the energy range being utilized.

Swift was launched into a low-Earth orbit on 20 Nov 2004 (Gehrels et al. 2004). It contains three instruments, the Burst Alert Telescope (BAT; Barthelmy et al. 2005) with an energy range of $15 - 350$ keV, the X-Ray Telescope (XRT; Burrows et al. 2005) with an energy range of $0.3 - 10$ keV, and the UV/Optical Telescope (UVOT; Roming et al.

2005) with a wavelength range of 170 – 650 nm. The BAT initially detects the GRB and transmits a 1 – 3 arc-min position to the ground within $\sim 12 - 45$ s. The spacecraft then autonomously slews to the GRB location within 20 to 75 s, at which time observations with the two narrow-field instruments XRT and UVOT begin.

As of 2005 August we have 28 long GRBs for which there exist *Swift*/XRT data beginning within 5 min of the GRB trigger. For this study we consider two of the best cases with known redshifts – GRB 050315 and GRB 050319. These are also "long" long bursts and so potentially allow us to test the relation between BAT and XRT fluxes during the near-overlap time of useful data with the two instruments. For these GRBs the XRT observations began 83.5s and 87s, respectively, after the GRB trigger, and these afford us the best possibility of studying, over a large dynamic range in flux, the detailed shape of the decay of the prompt emission.

2. Data Analysis

2.1. GRB 050315

A detailed analysis and discussion of the BAT and XRT data for GRB 050315 was carried out by Vaughan et al. (2005 = V05). Table 3 of V05 gives the detailed BAT and XRT spectral fitting parameters. From the BAT data $T_{90} = 96 \pm 10$ s and $T_{50} = 25 \pm 5$ s. The 15 – 350 keV fluence is 4.2×10^{-6} erg cm^{-2}, the photon index of the 1s peak spectrum is $\Gamma = 2.4 \pm 0.3$ (90% confidence, Krimm et al. 2005), while for T_{50}, $\Gamma = 2.02 \pm 0.07$ (V05). The redshift $z = 1.949$ (Kelson & Berger 2005) gives an isotropic equivalent total $\gamma-$ray energy 3.9×10^{52} erg, and the observed 0.2 – 10 keV BAT-extrapolated peak flux of $\sim 10^{-7}$ erg cm^{-2} s^{-1} translates into an initial 0.2 – 10 keV luminosity $\sim 10^{51}$ erg s^{-1}, using standard cosmological parameters ($H_0 = 72$ km s^{-1} Mpc^{-1}, $\Omega_M = 0.27$, $\Omega_\Lambda = 0.73$, Spergel et al. 2003). In the XRT, the photon index of the initial, bright phase ($t - t_0 \lesssim 300$ s) is $\Gamma = 2.5 \pm 0.4$, whereas for later times ($300 \text{ s} \lesssim t - t_0 \lesssim 10^4$ s) $\Gamma = 1.7 \pm 0.1$ (V05). V05 note that, if the steepening in the X-ray decay at 25000 s is interpreted as the jet break (Sari et al. 1999), then it implies a jet opening angle of $\sim 5°$, and a corrected total γ−ray energy of $\sim 3.1 \times 10^{49}$ erg.

2.2. GRB 050319

A detailed analysis and discussion of the BAT and XRT data for GRB 050319 was carried out by Cusumano et al. (2005 = C05). For the entire burst $T_{90} = 149.6 \pm 0.7$ s, and the 15-350 keV fluence over T_{90} was 1.6×10^{-6} erg cm^{-2} (C05). The redshift $z = 3.24$ (Fynbo et al. 2005) implies an isotropic equivalent energy in γ−rays of 3.7×10^{52} erg. In the XRT, the photon index of the initial, bright phase ($t - t_0 \lesssim 300$ s) is $\Gamma = 2.6 \pm 0.2$, whereas for later times ($300 \text{ s} \lesssim t - t_0 \lesssim 10^4$ s) $\Gamma = 1.7 \pm 0.1$ (C05), similar to GRB 050315. C05 find a steepening in the X-ray decay at 26000 s which, if interpreted as the jet break would imply a jet opening angle of $\sim 2.3°$, adopting nominal values for the ISM density (1 cm^{-3}) and efficiency of conversion of internal energy to γ−ray energy (0.2). This yields a beaming factor of ~ 1200, and a corrected total γ−ray energy of $\sim 3.1 \times 10^{49}$ erg.

Swift was slewing during GRB 050319, and the BAT trigger is disabled during this interval. The actual GRB began ~ 135 s before the originally reported trigger time t_0, which is now known to represent the onset of the last of the 4 spikes comprising the GRB. Nevertheless, in this study we utilize the original t_0 value, and restrict our attention only to the last spike, due to a simple physical consideration: Each individual spike comprising a GRB can be viewed in some sense as the observational consequence of a sudden injection of energy into a relativistic plasma, and the subsequent γ−ray and X-ray light curves provide us with information primarily about that one injection. Each individual spike would have a decay in X-rays associated with it, and in any given train of spikes constituting the entire GRB, only the most recent would be of relevance since the earlier ones would largely have decayed by the later time. This convention for GRB 050319 concerning t_0 is the same as that utilized by Chincarini et al. (2005), but different than that adopted by C05, who took the trigger time for the first spike in the GRB 050319 complex.

A potential caveat regarding our choice for t_0 regards the portions of the light curve after the initial steep decay. Even if the physics of that steep decay is dictated primarily by the final spike, the slope of the shallower decay that ensues is affected strongly by the choice of t_0. Insofar as the physics of the decay of that later portion of the light curve may well by better physically characterized by the choice of an earlier t_0, e.g., the trigger for the initial spike ($t_0 - 135$ s) or perhaps some average t_0 over the previous individual spikes comprising the entire GRB, one should not place too much emphasis on the value of the decay index for that shallower portion.

2.3. Methodology

We calculate the decay of the prompt emission as follows: We first extract the BAT light curve in the energy range $15 - 350$ keV, then fit a power law to the spectrum over the central 50% of the fluence, i.e., T_{50}, then we extrapolate this emission into the $0.2 - 10$ keV energy range. The conversion factor for each GRB is calculated using the flux calculator tool `PIMMS`. The power law index inferred from the $\gamma-$ray spectrum, with its associated 1σ error, is propagated through as error bars that add in quadrature to the Poisson flux errors. In addition to the formal systematic errors, one also has extrinsic errors of uncertain magnitude stemming from the assumption of one continuous power law over a broad spectral range. For bursts with a photon index close to 2, i.e., equal emission per decade in frequency, or in other words a flat spectrum in terms EF_E versus E, this error would be less important. For times close to t_0 that are of interest in this study, the exact value of t_0 determines the logarithmic decay slope. In this work we take the same $t_0(\mathrm{XRT}) = t_0(\mathrm{BAT}) = t_0(\mathrm{trigger})$, the GRB trigger time.

GRB 050315: A detailed description of the XRT data reduction is given in V05. The XRT count rate of GRB 050315 at the start of the pointed observation was in excess of 100 ct s^{-1} ($\sim 3 \times 10^{-9}$ erg s^{-1} cm^{-2}), resulting in heavy pile-up in the PC-mode data. Ordinarily the XRT camera would have switched to a different mode (e.g., WT or Photodiode modes) in order to accommodate such a high rate, but the XRT was in Manual State at the time of the trigger and remained in PC mode during the early observations.

The most obvious effect of pile-up is an apparent loss of counts from the center of the image, compared to the expected Point Spread Function (PSF). This effect was used to determine at what count rate pile-up can no longer be ignored, by fitting the image radial profile with a PSF model and successively ignoring the inner regions until the model gave a good fit. The region over which the PSF model gave a good fit is the region over which pile-up may be ignored. In the present analysis the central 8 pixels (radius) were ignored for (observed) count rates between 1 and 5 ct s^{-1}, and the central 14 pixels (radius) were ignored for higher count rates. (Note one pixel corresponds to 2.36 arcsec.) After excluding the center of the image the fluxes were corrected simply by calculating the fraction of the integrated PSF used in the extraction. (These results were obtained using only mono-pixel events, i.e. `grade = 0`, which should be least affected by pile-up.) A light curve was extracted over the $0.2 - 10$ keV band, binned such that there were 25 source events per bin, and a background was subtracted using a large annulus concentric with the source extraction region. Error bars were calculated assuming counting statistics.

GRB 050319: A detailed description of the XRT data reduction is given in C05. The XRT count rate values were obtained extracting events ($0 - 12$ grade; $0.2 - 10$ keV) in a circular region. Pileup in the first part of the observation was then corrected by excluding the central pixels, fitting a PSF model to the wings of the emission, and rescaling the central portions using the instrumental PSF to recover the lost counts. Events were binned in order to have a constant S/N of 5. The light curve was then fitted with a broken power law with two temporal breaks. The conversion factor from count rate to flux was obtained by performing the spectral analysis of the whole XRT spectrum and by comparing the unabsorbed flux in the $0.2 - 10$ keV band with the average count rate in the same energy band. This correction factor was then applied both to the XRT light curve and the best fit model.

Figures 1 and 2 show the composite light curve decays for the $0.2 - 10$ keV fluxes, extrapolated from the BAT and measured by the XRT. The dot-dashed line in each plot indicating a logarithmic slope of -3 is not a fit to the data, but intended to be illustrative. Up to ~ 250 s after burst onset, one sees a steep decay in the light curve. After this time the slope flattens abruptly, demarcating the time at which the prompt emission gives way to the early afterglow.

For GRB 050315, exponential decays give a better characterization than a single power law decay for the BAT and XRT light curves for $t - t_0 \lesssim 300$ s. The $e-$folding decay times are $\tau(\mathrm{BAT}) \simeq 24 \pm 2$ s and $\tau(\mathrm{XRT}) \simeq 35 \pm 2$ s; after taking into account the cosmological $(1 + z)$ time dilation, these transform to $\tau(\mathrm{BAT}) \simeq 8 \pm 1$ s and $\tau(\mathrm{XRT}) \simeq 12 \pm 1$ s at $z = 1.95$ (V05). This slight difference between BAT and XRT is consistent with modest hard-soft evolution.

As discussed in detail in V05, the $t - t_0 \lesssim 10^3$ s XRT light curve for GRB 050315 evolves through flat $\rightarrow$ steep $\rightarrow$ flat phases (followed by a second steepening seen in later orbits). This first part of the light curve, until the end of the steep descent at ~ 300 s, can be modeled either using a broken power law or an exponential decay. (The second break and additional flat power law accounts for the true afterglow emission.) A single power law for the steep decay is not acceptable. The two solutions are (i) a break in the power law from $n = 2$ to $n = 5$ at $t - t_0 \sim 120$ s (V05, Table 2) or (ii) an exponential decay. Both models give excellent fits; formally the exponential model gives a worse χ^2 fit, but has two fewer free parameters. It may be more appealing due to its simplicity than an arbitrary power law break. Exponential decays also avoid the problem of the choice of t_0 which has a strong influence on the derived decay slope n.

3. Discussion

We have presented convincing evidence that for two GRBs observed by *Swift*, the prompt emission can be seen in X-rays up to about 300 s after the GRB trigger. In addition, the light curves from the BAT and XRT connect continuously, without there being a significant offset. For completeness, we note that not all such GRBs for which complete early-time XRT observations exist share this property. For instance, Tagliaferri et al. (2005) present data for two other GRBs, GRB 050126 and GRB 050219a, for which the early time XRT light curve lies significantly above an extension of the BAT 0.2 – 10 keV (extrapolated) light curve. It is possible that strong spectral evolution, and/or and non-power-law spectral shape, may invalidate the simple prescription we and others have adopted of extrapolating the BAT flux into the XRT bandpass. Another possibility is that a flare occurred in the X-ray bandpass (Burrows et al. 2005), with the maximum located before the XRT observation began (i.e., at $t < t_0 + 100$ s). All five of the GRBs studied by Tagliaferri et al. show XRT light curves in which the initial steep decay gives way at later times to a more shallow decay, thereby supporting the idea of the initial X-ray flux as representing a continuation of the prompt emission. Campana et al. (2005) present an XRT light curve for GRB 050128 that shows evidence for flat decay at $t \lesssim 300$ s, followed by a steeper decay out to $t \gtrsim 10^5$ s. Chincarini et al. (2005) study the XRT decay light curves for seven GRBs and present evidence for at least two classes: those with a steep initial decay and those with a shallow initial decay. It is difficult to form a general hypothesis of the early X-ray behavior based on so few examples (cf. Nousek et al. 2005, Zhang et al. 2005), but it may be that for most GRBs the intrinsic tendency is for the prompt decay up to ~ 300 s to be steep, as in GRB 050315 and GRB 050319, whereas for others a variety of systematic effects, such as viewing geometry, rapid cooling of the ejecta, and evolutionary effects such as the shifting of the synchrotron cooling frequency ν_c out of the observational (XRT) bandpass, conspire to distort and hence obscure this simple, underlying behavior.

Within the theoretical framework of the expanding, relativistic blast wave model in which synchrotron emission from relativistic electrons dominates, the power law decay index for the decaying light curve depends only on the index of the power-law distribution of electrons with energy, the density stratification of the medium into which the burst propagates, and the location of the frequency of the observing bandpass relative to ν_c. The most straightforward interpretation of the steep initial decay for GRB 050315 and GRB 050319 may be the "curvature effect" associated with the time delay from high latitude emission within the relativistic ejecta. This effect is due to the fact that, when the internal shocks stop radiating, an observer viewing the emission close to the primary velocity vector of the ejecta sees emission from larger and larger viewing angles due to the Doppler delay effect (Kumar & Panaitescu 2000=KP00, see Dermer 2004 for a more complete derivation).

A simple physical understanding for the curvature effect is as follows. If the GRB emission terminates abruptly at some radius r and Lorentz factor γ, then the perceived flux $F_\nu(t) \propto F^{'}_{\nu'}(d\Sigma/dt)D^2$, where $F^{'}_{\nu'} \propto \nu^{'-\beta}$ is the surface brightness in the comoving frame at frequency $\nu^{'} = \nu/D$, $d\Sigma = 2\pi r^2 \theta d\theta$ is the differential area contributing to the radiation received in an interval dt in the observer's frame, θ is the angle of the fluid element from which radiation is received at $t = r\theta^2/2$ (implying $dt \propto \theta d\theta$), and the relativistic Doppler factor $D = 2/(\gamma\theta^2) \propto t^{-1}$. The expressions for $t(\theta)$ and $D(\theta)$ assume $\theta >> \gamma^{-1}$. The factor D^2 accounts for beaming of the emission from a relativistic source. Simplifying the flux expression yields $F_\nu(t) \propto \nu^{-\beta} t^{-2-\beta}$. where β is the energy spectral index, i.e., Γ(BAT)-1. The BAT energy spectral index Γ(BAT)-1 is close to 1 for both GRBs, consistent with the value required to produce a $n = 3$ decay law.

As noted in the previous section, for GRB 050315 an exponential decay fits better than a power law decay, indicating that at least one of the underlying assumptions entering into the power law derivation is not fulfilled. An exponential decay from the large-angle GRB emission would be obtained if the comoving frame energy band which is Doppler-shifted to the observer's $0.2 - 10$ keV band were above the cooling frequency only if the outflow were tightly collimated, and we see its boundary. If the GRB emission stopped at t_0, then at $t - t_0 \sim 100$ s, we see the emission from an angle $(100\ \mathrm{s}/t_0)^{1/2}\gamma^{-1}$ $(< 2\gamma^{-1})$ because the arrival time for the large-angle emission increases as the square of the angle from whence that emission arises. Hence, the large-angle GRB emission would exhibit an exponential decay (above the cooling frequency) only if the jet is narrower than 1 degree. On the other hand, if the break in the XRT light curve at $t - t_0 \simeq 2 \times 10^5$ s represents the jet break, the observed $E_{\rm iso}$ value for GRB 050315 implies a jet opening angle $\theta_0 \simeq 5°$ (V05), which would be inconsistent with this explanation.

The transition at $t \simeq 250 - 300$ s in our reference frame to a much flatter decay law in GRB 050315 and GRB 050319 may provide a clue to the time scale for the relativistic shell to decelerate as it moves into the ISM gas. KP00 give the shell deceleration time, measured in the local rest frame at a given z, as 100 s $E_{52}^{1/3}(1-\eta)^{1/3}(\eta n_0 \gamma_2^8)^{-1/3}$, where E_{52} is the isotropic equivalent $\gamma-$ray energy in units of 10^{52} erg, η is the efficiency factor for converting internal energy of the explosion into $\gamma-$ray energy, $\gamma_2 = \gamma_0/10^2$ is the initial Lorentz factor of the ejecta, scaled to 100, and n_0 is the number density of the ISM. (The deceleration time measured in the comoving ejecta frame is larger by a factor $\sim 2\gamma^2 \simeq 10^4$.) The times at which the initial steep XRT decays abruptly give way to much shallower decays are ~ 100 s in the frame of an observer at a cosmological redshift $z = 1.95$ for GRB 050315 (~ 300 s in our reference frame), and ~ 60 s at $z = 3.2$ for GRB 050319 (~ 250 s in our frame). The fact that the time of our flattening is consistent with the theoretical deceleration time adds strength to the standard model of relativistic ejection and prompt emission, followed by deceleration and afterglow emission. As a potential caveat to this interpretation, Zhang et al. (2005) carry out detailed numerical calculations of the curvature effect and find that the observed transition time between steep and shallow decay may only be an upper limit to the deceleration time. The fireball could well be decelerated earlier, but the deceleration signature (marked by a rising phase followed by a $n \simeq -1$ decay) could be buried beneath the steep-decay component. Zhang et al. (2005) use the observed transition times for GRB 050315 and GRB 050319 to set lower limits on the initial fireball Lorentz factors.

4. Conclusion

We present combined BAT/XRT data from two GRBs observed by *Swift* for XRT observations began within 100 s of the BAT trigger. The data presented herein give a clear indication that the prompt emission and late afterglow emission are two distinct components. The early X-ray afterglow is the tail of the prompt $\gamma-$ray emission, and the late X-ray afterglow is the normal forward shock afterglow. This lends support to the prevailing notion that prompt emission is from internal shocks rather than external shocks.

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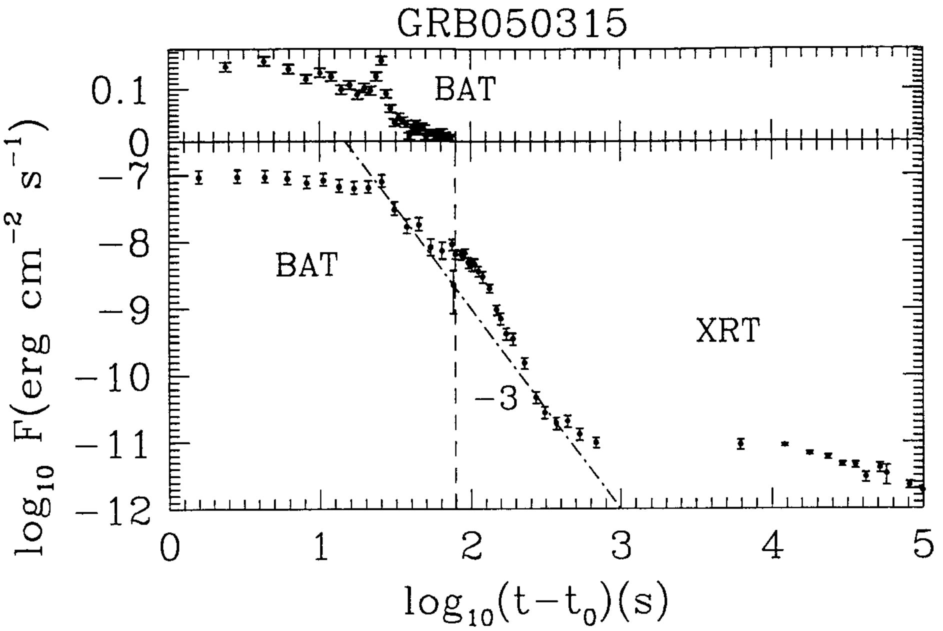
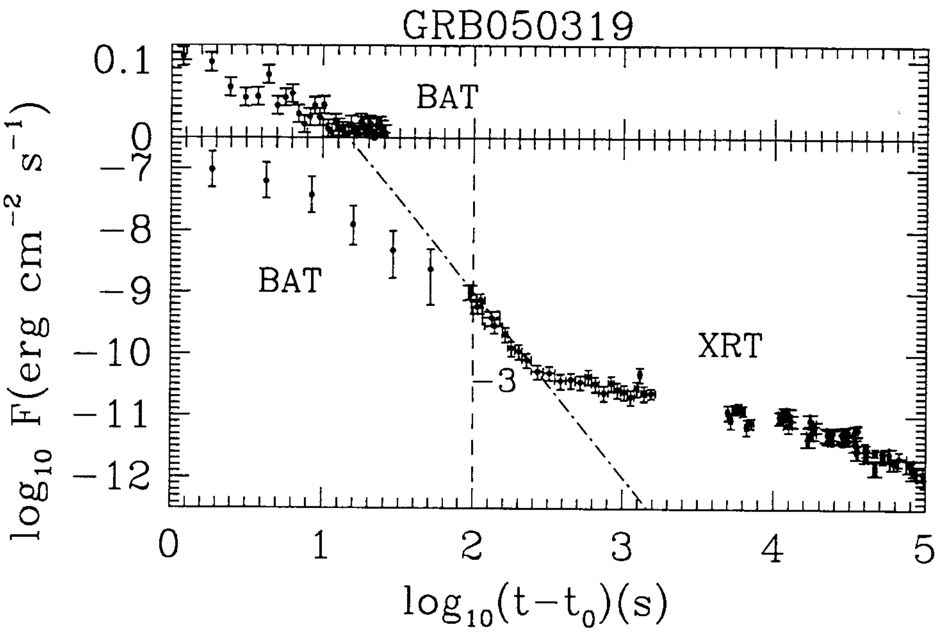
Figure Captions

Fig. 1.— The combined BAT/XRT 0.2 – 10 keV light curve of GRB 050315. The small panel on top shows the BAT data on a log-linear scale, in units of background subtracted 15-350 keV flux per fully illuminated detector. The main, large panel shows the combined BAT and XRT data. The vertical dashed line shows the approximate time of the start of XRT observations, and the dot-dashed line indicates a logarithmic decay slope of -3.

Fig. 2.— The combined BAT/XRT 0.2 – 10 keV light curve of GRB 050319. The conventions are the same as in Fig. 1.


GRB050315
BAT
0.1
0
−7
−8
−9
−10
−11
−12
BAT
XRT
−3
0
1
2
3
4
5
log₁₀ F(erg cm⁻² s⁻¹)
log₁₀(t−t₀)(s)


GRB050319
BAT
BAT
XRT
−3
0.1
0
−7
−8
−9
−10
−11
−12
0
1
2
3
4
5
$\log_{10}$ F(erg cm^{-2} s^{-1})
$\log_{10}(t-t_0)$(s)